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This fellowship supported Lynn Nelson until the completion of her PhD in 1997. The section below entitled "Modelocking of Thulium-doped and Erbium-doped Fiber Lasers" summarizes her research. For the remainder of the period, it supported Erik Thoen in his SM research on "Ultrafast Gain-Index Coupling in InGaAsP Diode Lasers" and his PhD research on "Passive Modelocking of a Waveguide Laser with Semiconductor Saturable Absorbers."

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Final Report to the Army Research Office
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Modelocking of Thulium-doped and Erbium-doped Fiber Lasers

Passive modelocking of thulium-doped and erbium-doped fiber lasers was investigated using the technique of polarization additive-pulse modelocking (P-APM). With this technique, a self-starting, modelocked Tm^{+3}-doped fiber laser was demonstrated with 360 to 500 fsec pulses tunable from 1.8 to 1.9 μm, the largest tuning range yet demonstrated from a rare-earth doped fiber. This laser operated in the soliton regime due to the large anomalous group velocity dispersion (GVD) of the fibers at 1.8 μm.

Frequency doubling of a stretched-pulse Er^{+3}-doped laser to 775 nm where the pulses can be used as a seed for a Ti:sapphire regenerative amplifier was also demonstrated. This laser incorporated segments of fiber with normal as well as anomalous GVD to avoid operation in the soliton regime. Compressed fundamental pulses of 100 fsec and 2.7 nJ were obtained, and three nonlinear crystals, β-BaB_2O_4(BBO), $KNbO_3$ (potassium niobate) and LiB_3O_5 (LBO), were evaluated for frequency doubling, Nearly transform-limited pulses at 771 nm with average powers of 8.7 mW were obtained with a 1-cm BBO crystal, corresponding to conversion efficiencies of up to 10%. Frequency resolved optical gating (FROG) measurements were performed on both the fundamental and doubled pulses to better characterize the laser.

The effect of linear birefringence on P-APM was explored through numerical simulations for the case of standard fibers, where the two are of the same order. Although reduced by the birefringence, pulse shaping still occurred and there was no inherent periodicity due to the fiber beat-length. Measurements of birefringence and temperature sensitivity of both standard and polarization maintaining (PM) fibers were also performed.

Experimental work toward an environmentally stable Er^{3+}-doped fiber laser included two different schemes. The first design was comprised of only PM fiber, but stable modelocking was prevented by the temperature dependence of the PM fiber. The second scheme, the sigma laser, was a traveling-wave cavity that used both non-PM and PM fiber. Environmental stability was achieved by canceling changes in linear phase bias in the non-PM fiber and using linear polarization along one of the axes in the PM fiber.

Stretched-pulse operation of the sigma laser was ultimately achieved with sub-110 fsec, >1 nJ, pulses generated directly from the cavity.

Publications:

1. L.E. Nelson, E.P. Ippen and H.A. Haus, "Broadly Tunable Sub-500 fs Pulses from an Additive-Pulse Mode-Locked Thulium-Doped Fiber Ring Laser", Appl. Phys. Lett. 67, pp. 19-21, 1995.
2. L.E. Nelson, S.B. Fleischer, G. Lenz and E.P. Ippen, "Efficient Frequency Doubling of a Femtosecond Fiber Laser", Optics Lett. 21, pp. 1759-1760, 1996.
3. D.J. Jones, L.E. Nelson, H.A. Haus and E.P. Ippen, "Diode-Pumped Environmentally Stable Stretched-Pulse Fiber Laser", IEEE J. Quant. Electron., 3, pp. 1076-1079, 1997.
4. L.E. Nelson, D.J. Jones, K. Tamura, H. Haus and E.P. Ippen, "Ultrashort-Pulse Fiber Ring Lasers", Appl. Phys. B., 65, pp. 277-294, 1997.
5. L.E. Nelson, "Modelocking of Thulium-doped and Erbium-doped Fiber Lasers," PhD Thesis, MIT, Department of Electrical Engineering and Computer Science, February, 1997

Ultrafast Gain-Index Coupling in InGaAsP Diode Lasers

Heterodyne femtosecond pump-probe measurements were performed to determine the ultrafast nonlinear optical response of InGaAsP quantum well semiconductor optical amplifiers at 1.55 μm. These responses provide a measure of the various ultrafast, nonequilibrium carrier dynamics in these devices and well as coefficients for all-optical switching. With a wavelength-tunable femtosecond optical parametric oscillator (OPO) we were able to study the various physical contributions to this response as a function of wavelength.

Theoretical work on the pump-probe measurement technique for gain dynamics in the presence of index of refraction dynamics suggested that the gain and index signatures included artifacts produced by the coupling produced by frequency shifts and spectral filtering. Both gain and index dynamics contribute to each other's measurement with a term that is proportional to the time derivative of the response and the spectral slope of the linear transmission function. To evaluate this effect, we used a femtosecond heterodyne detection method in conjunction with the (OPO) pulses. We measured both gain and index response, as a function of polarization, for wavelengths corresponding to gain, transparency and absorption in the diode amplifiers. An iterative fitting procedure, using both gain and index results to account for the coupling artifact, was used to extract time constants for the equilibration of carrier distributions (delay in carrier heating, or spectral holeburning) and the subsequent cooling of the distributions to the lattice temperature (the carrier heating recovery). The results suggest that, even when the coupling artifact is accounted for, the initial fast equilibration component is still a significant component of the measured response.

With our heterodyne technique, we were also able to make careful measurements of the alpha parameter (ratio of index change to gain change) associated with the intraband carrier heating. Experiments performed at different current densities and different photon energies with respect to the transparency point produced the first determination, as a function of wavelength, of the alpha parameter associated with carrier heating.

Publications:

1) K. L. Hall, E. R. Thoen and E. P. Ippen, "Nonlinearities in Active Media." Nonlinear Optics in Semiconductors II, Semiconductors and Semimetals, Vol 59, Academic Press 1998

Passive Modelocking of an Er/Yb Glass Waveguide Laser with a Semiconductor Saturable Absorber

Semiconductor saturable absorbers have been used before to passively modelock a variety of fiber lasers; but these devices have been limited to operation at relatively low repetition rates because of Er-doping density limits in fiber. In this work we have demonstrated saturable Bragg reflector (SBR) modelocking of a highly doped waveguide laser that should be scalable to high repetition rates. It was achieved with 150-250 mW of pump power at 980 nm and with a dielectric filter to inhibit lasing at the narrow-band point of peak gain in Er^{3+}. Pulses were obtained with 1 psec durations, 2 nm in spectral width and 0.63 mW of average power.

Saturation fluence measurements of our SBR's made with femtosecond pulses revealed about 10% saturable loss and about 5% nonsaturable loss. Dynamically, in pump-probe experiments we observe a partial, fast recovery within 350 fsec followed by a slower recovery over 32 psec. Thus, the SBR's can both self-start the laser and shape femtosecond pulses. At the intensity levels in waveguide and fiber lasers, however, the experiments show that higher-order, two-photon absorption causes significant intensity limiting. This may have the undesirable effect of preventing the pulses from getting as short as they might otherwise. We have discovered that it also has a positive effect; it suppresses Q-switched modelocked operation of the system and thereby helps stabilize cw- modelocking. This latter property is particularly important in short cavity, high rep rate lasers which are more prone to Q-switching.

References:

1) E.R. Thoen, E.M. Koontz, D.J. Jones, P. Langlois, F.X. Kaertner, E.P. Ippen, L.A. Kolodziejski and D. Barbier, "Picosecond pulses from a Er/Yb Waveguide Laser Passively Modelocked with a Semiconductor Saturable Absorber," submitted to CLEO '99.
2) E.R. Thoen, E.M. Koontz, D.J. Jones, P. Langlois, F.X. Kaertner, E.P. Ippen, L.A. Kolodziejski and D. Barbier, "Suppression of Instabilities and Pulsewidth Limitation by Two-photon Absorption in Modelocked lasers," submitted to CLEO '99.